ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 4 (2011) 5669–5676
Energy Procedia
www.elsevier.com/locate/procedia

GHGT-10

Assurance monitoring approach for the Heartland Area Redwater Project (HARP) geological CO_2 storage project, Alberta, Canada.

Brydie, J. R.[a*], Faught, R. L[a], Trottier, S.[a] Macyk, T.[a], Dmetruik, J.[b] and Krawec, T.[c]

[a]*Alberta Innovates – Technology Futures (AITF), 250 Karl Clark Road, Edmonton, T6N 1E4 , Canada*
[b] *ARC Resources Ltd., Box 1090, Redwater, T0A 2W0, Canada*
[c]*ARC Resources Ltd., 2100-440 2 Avenue Southwest, Calgary, T2P 5E9, Canada*

Abstract

The Heartland Area Redwater Project (HARP) aims to inject and geologically store up to a gigatonne of captured CO_2 derived from Alberta's Industrial Heartland. The storage formation will be the vast water leg of the Devonian Redwater-Leduc carbonate reef structure, also host to Canada's third largest conventional oil pool. Extensive characterization activities, including geological, geophysical, hydrogeological, geochemical, soil, atmospheric studies and land management practices are currently nearing completion. Combined information from these studies is allowing for the integration and development of conceptual and numerical models. Intensive activity is currently focused upon a small pilot site within the water leg of the reef. Should this pilot program prove to be successful, CO_2 injection, and the associated monitoring program, may be scaled up to allow an annual injection of up to 1 million tonnes of CO_2. The integration of near surface characterization and monitoring along with injection formation characterization (*e.g.* fluid sampling and time-series geophysics) and well integrity studies have guided the design and implementation of the HARP assurance monitoring program. Field data acquisition and interpretation are currently ongoing to allow a pre-operational phase, pilot-scale, assurance monitoring baseline to be established. Public consultation and stakeholder involvement with the project forms a key component in both implementing the program, and allowing for sustainable agricultural and industrial development within the Alberta Industrial Heartland area.

Keywords: *Heartland Area Redwater Project; HARP; MMV; CO_2 storage; Assurance monitoring; Alberta*

1. Introduction

The geological storage of CO_2 in CO_2 enhanced oil recovery operations and in deep saline aquifers is currently being investigated in Alberta to reduce the total greenhouse gas emissions produced by Alberta's oil sands operations, refineries, and chemical, cement and power plants. This reduction in greenhouse gas emissions will allow for sustainable hydrocarbon refining and usage, as well as gaining time to allow the implementation of both clean and renewable energy technologies. To this end, the Heartland Area Redwater Project (HARP) aims to inject and geologically store several million tonnes of captured CO_2 derived from Alberta's Industrial Heartland. The geological storage formation will be the vast water leg of the Devonian Redwater Leduc carbonate reef structure, also host to Canada's third largest conventional oil pool. In addition to geology and hydrogeology, the depth, usage history and integrity of hydrocarbon wells have been evaluated for the entire reef footprint [1]. Near surface potable water wells have been evaluated, and their characteristics added to the evolving site scale conceptual model.

This paper describes the development of the HARP CO_2 pilot injection site conceptual model, and how this model has influenced the design and implementation of site-scale assurance monitoring activities within the broader HARP

* Corresponding author. Tel.: +1-780-450-5102; Fax: +1-780-450-5083. *E-mail address*: james.brydie@albertainnovates.ca.

doi:10.1016/j.egypro.2011.02.559

measurement, monitoring and verification (MMV) program. More information about the project can be found in Gunter *et al*. [2, 3] and Bachu *et al*. [4].

2. HARP Site Characteristics

The development of a conceptual model for the HARP project included the integration of regional- and local-scale geology, hydrogeology, hydrocarbon wells, potable water wells, soils, vegetation, climate, air quality and existing sources of CO_2 which form components of the overall MMV baseline for the site. To this end, a number of study areas were defined during the initial phases of the HARP project, depending upon the type and availability of information required and the nature of study being conducted. The HARP "regional-scale study area (RSSA)", delimited by the dark bounding box in Figure 1, covers a large area ranging from Township 50 to 65, and Range 2 to 27, west of the 4th Meridian (W4M) (40,000 km^2) (Figure 1). The RSSA was defined to allow regional-scale geological and hydrogeological mapping and characterization, providing context for CO_2 injection and long term storage within the Redwater-Leduc reef. Within the regional study area, a smaller "local-scale study area (LSSA)" was defined which covers an area from Township 55 to 58 and Range 20 to 24 (W4M) (Figure 1). The LSSA, which is rectangular and roughly 1,900 km^2 in size to encompass the Redwater reef, was defined to allow the detailed assessment of the characteristics, relationship and hydraulic communication between deep saline aquifers and near surface potable aquifers [2, 3, 4].

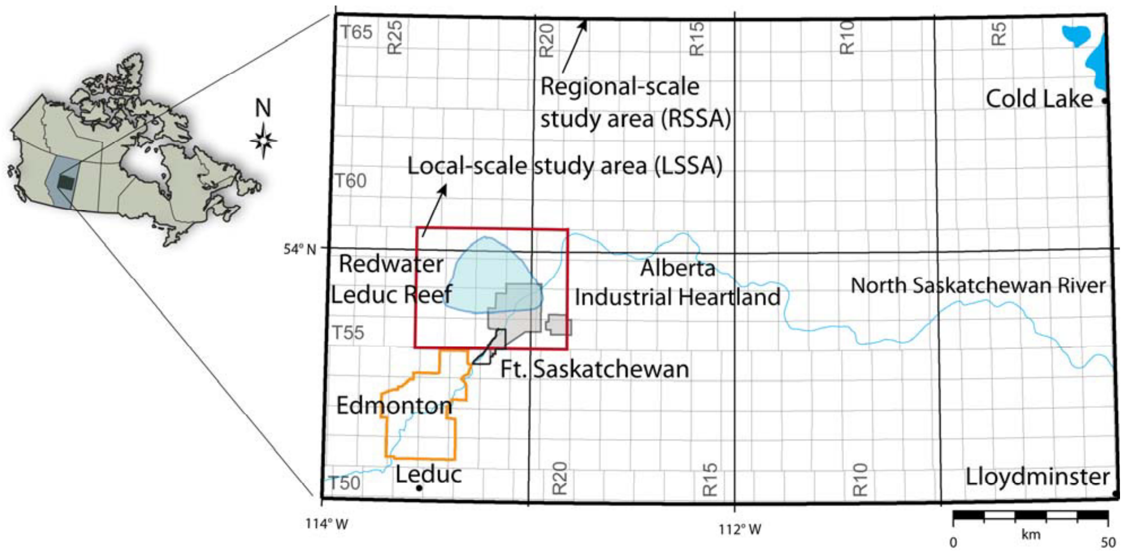

Figure 1: Location of the HARP regional-scale study area (RSSA) and local-scale study area (LSSA) in relation to Edmonton and other town sites. The Redwater Leduc reef surface footprint is shown in relation to the town of Redwater and Alberta's Industrial Heartland (after Bachu et al., 2010).

2.1 Site environmental, geological and hydrogeological context of the HARP LSSA

This section provides a summary of the LSSA, including climatic conditions, surface features, soils, geology and hydrogeology, and provides context for the smaller pilot-scale study area.

Climatic conditions are within the Dfb boundary which consists of long cool summers and severe winters with mean annual temperatures ranging from -10 to -40°C in winter and from 21 to 28°C in the warmest months [5, 6]. Mean annual precipitation has been recorded as 478 mm, with a calculated mean annual evapotranspiration of 517 mm [7, 8, 9, 10, 11], each with overlapping errors of both measurement and calculation. Prevailing wind direction is generally from the west for most seasons, and from west and south during winter months [12]. Surface features in the LSSA include Township and Range roads, surface power lines adjacent to roads, settlements, farm buildings, acreages and supporting rural infrastructure. Across the Redwater-Leduc surface footprint (approximately 600 km^2), a wide variety of soil types are present including luvisols, brunisols, mesisols, gleysols, chernozems and solonetz types [13, 14].

Extensive geological and hydrogeological assessments and mapping of aquifers and aquitards present for the entire stratigraphy of the HARP LSSA, from the Precambrian basement to surface, were recently carried out [2, 3]. Geological assessments included structural and isopach mapping from the Basal Cambrian sandstone, the first unit on the top of the crystalline Precambrian basement, upwards through the Redwater-Leduc reef (i.e. the target CO_2 storage formation), and all of the overlying formations to the top of unconsolidated surficial deposits present (Figure 2) [15].

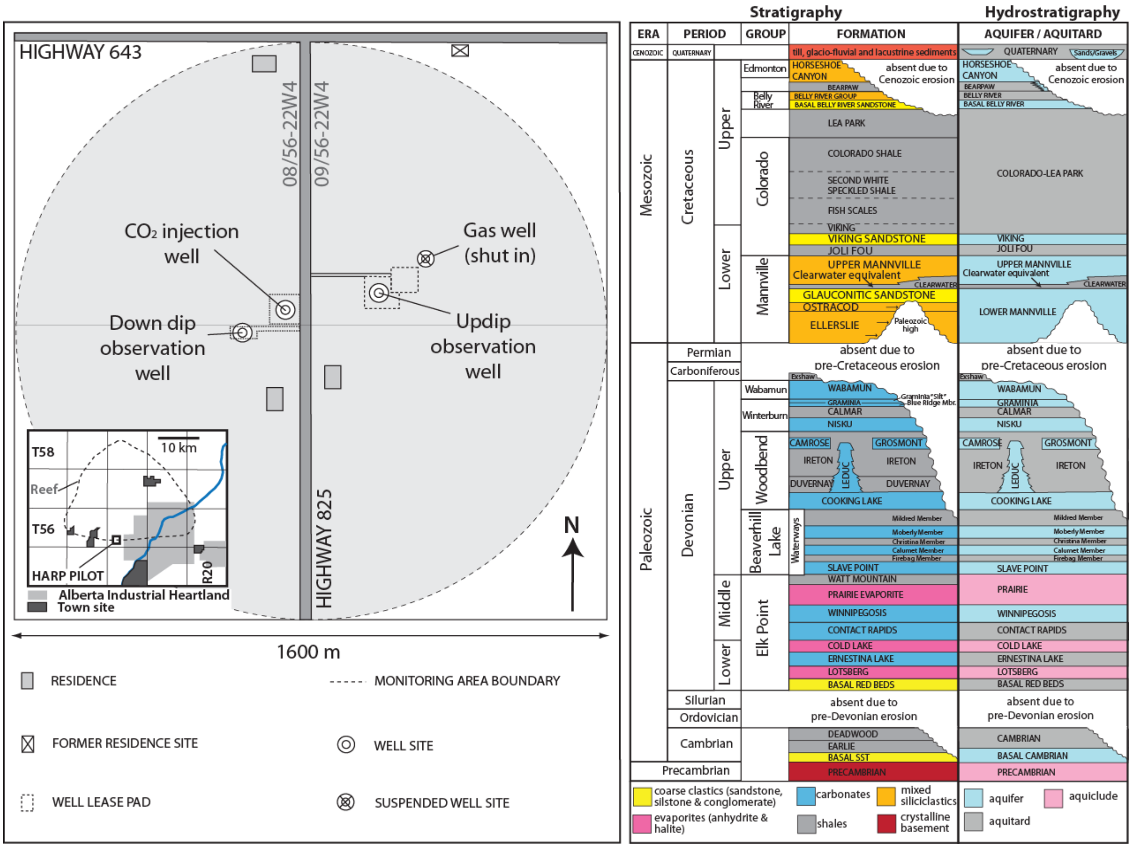

Figure 2: Schematic map of the HARP site-scale study area (SSSA) in relation to local town sites, the Redwater-Leduc reef footprint and Alberta's Industrial Heartland. Lithostratigraphic and hydrostratigraphic columns are provided for context (taken from Bachu et al., 2010).

In summary, a series of siliciclastic and carbonate formations form saline aquifers between the PreCambrian basement rocks and the ground surface, separated from each other by competent shale and evaporite strata (aquitards and aquicludes) which form effective caprock formations [2, 3, 4]. An extensive pre-Cretaceous erosional surface forms an unconformity overlain by Cretaceous age mixed siliciclastics, sandstones and thick shales. In the near-surface environment, the Lea Park shale is conformably overlain by deltaic and fluvial sediments, predominantly sandstone, of the basal Belly River sandstone. This sandstone is conformably overlain by coals of the McKay Coal Zone which are laterally continuous across the entire LSSA. These coals, comprised of up to six separate seams, physically separate the Basal Belly River Sandstone from the undifferentiated Upper Belly River Group, which is comprised of a series of mixed fluvial siliciclastics [16]. Additional discontinuous coal seams, belonging to the Taber Coal Zone, are present stratigraphically higher in the Upper Belly River Group. Marine shales and siltstones of the Bearpaw Formation conformably overlie the Upper Belly River [17]. The stratigraphically-uppermost unit at the top of the bedrock in the study area is the Horseshoe Canyon Fm. of the Edmonton Group. The lower part of the Horseshoe Canyon Fm. was deposited as marginal-marine sandstones that prograded eastward over the Bearpaw shales [11, 18]. Cenozoic erosion of the westwardly dipping Upper Belly River Group, Bearpaw and Horseshoe Canyon formations resulted in these formations forming the current bedrock topography. Surficial deposits are composed of a complex mixture of pre-glacial, peri-glacial and post-glacial sediments which have been deposited on the sub-Cenozoic Unconformity [10]. Present-day rivers, such as the North Saskatchewan River, have in some areas incised down through the Cenozoic sediments into the Cretaceous bedrock, giving rise to the present day landscape.

Hydrostratigraphic classification of all aquifers and aquitards (e.g. caprocks) within the succession was based upon both rock properties and associated hydraulic properties and chemistry of deep saline to near surface potable groundwater aquifers. Multiple barriers within the stratigraphy separate deep saline aquifers from each other, confirmed by differences in aquifer pressure, flow regime and chemical characteristics of formation waters [2, 3, 4]. Potable aquifers within the undifferentiated Upper Belly River Group formations are hydraulically and chemically distinct from the underlying saline aquifers, such as the Basal Belly River aquifer. Bedrock channels heavily influence surficial sand and gravel aquifer distribution. Following extensive groundwater database culling and mapping, water level, salinity and groundwater chemistry in the local-scale study area were found to be consistent and support a hydrogeological conceptual model where meteoric waters recharge aquifers within the surficial deposits and immediately underlying the undifferentiated Upper Belly River aquifer, with which they are in direct hydraulic contact in the eastern portion of the study area. The hydraulic head distribution within surficial aquifers mirrors study area topography. Groundwater discharge is predominantly into the Beverly Channel aquifer and North Saskatchewan River. Till units form local discontinuous barriers to groundwater flow, but in general, much of the local-scale study area is in recharge, with groundwater chemistry of surficial aquifers and the underlying Upper Belly River aquifer being directly comparable to the expected composition of fresh-meteoric recharge water. Groundwater within the surficial deposits tends to be chemically hard, and ranges between Ca-HCO_3 and Na-HCO_3 in type, becoming progressively more Na-HCO_3 and Na-Cl rich with greater depth and residence time in the aquifer. Magnesium also forms a significant component in some waters, contributing to chemical hardness. This model is consistent with the conclusions of previous hydrogeological mapping [7, 8, 9, 10, 11] and specific small-scale groundwater assessments within the local Beverly Channel aquifer [20, 21] and environmental impact assessments carried out in Alberta's Industrial Heartland area [22, 23].

<u>Hydrocarbon wells, potable water wells and CO_2 storage related wells</u>

Across the entire Redwater-Leduc reef footprint, a total of 1323 hydrocarbon-related wells exist, with at least 1280 of these wells reaching the oil leg of the Redwater-Leduc reef.

Records from a total of 4638 water wells were evaluated as part of this study to determine potable groundwater chemical characteristics. Following extensive data culling and quality checks, a total of 156 water well samples were found to be derived from specific aquifers and of sufficient data quality to characterize near-surface conditions. A total of 89 wells were retained for mapping hydraulic properties across the LSSA, and only 76 wells were retained for mapping water chemistry. These data included groundwater samples taken from 11 wells in December 2009 within a 1500 m radius of the proposed CO_2 injection well location.

2.2 HARP Site-Scale Study Area (SSSA)

Within the LSSA, an even smaller study area has been defined close to the planned pilot CO_2 injection well and nearby deep observation wells. This "site-scale study area (SSSA)" has a circular footprint with a radius of 800 m centred upon the proposed CO_2 injection location (Figure 2). The areal footprint of the SSSA was based upon the numerically predicted size and dispersion of the CO_2 plume following the injection of 100,000 tonnes of supercritical CO_2 [24, 25]. The pressure front will likely extend farther than this distance within the storage formation. The area also lies immediately west of Alberta's Industrial Heartland, which hosts a variety of chemical and petrochemical facilities. The remainder of this paper discusses specific aspects only of the shallow hydrosphere, biosphere and atmosphere within the areal footprint of the SSSA and from the ground surface to the base of the Cooking Lake aquifer (Figure 2).

Characterization of the SSSA resulted in detailed high resolution information about potable aquifers, water wells, hydrocarbon wells, soils, vegetation, land management practices and local air quality. This information forms the basis for risk assessment and associated monitoring strategies for detection of CO_2 in the unlikely case of leakage. Potable water wells, the pilot CO_2 injection well, two deep CO_2 observation wells and a single gas well (currently shut-in and non-operational) are key monitoring targets. Land management practices are also being monitored across the SSSA, as agricultural practices such as tilling and crop growing affect the seasonal soil-derived CO_2 concentration and flux. Crops are typically grown in rotation within each quarter section of land (i.e. 640000m^2) and have recently included seed potatoes, canola, wheat and barley. Soil productivity and potable water quality are of primary importance to local land owners, and, as a result, extensive soil, soil gas and groundwater sample collection and analyses are ongoing, and being used to generate baseline physical and chemical conditions prior to any CO_2 injection activities in the area.

A single CO_2 injection well and two observation wells will exist within the SSSA. All three wells will penetrate the Redwater-Leduc reef (Figure 2), and as such, will form key monitoring targets within the HARP study area as they provide potential CO_2 migration pathways from the geological storage formation to the surface in the unlikely event there is a CO_2 leak. A relatively shallow gas well, originally completed and producing from the Upper Mannville Formation and currently shut-in, forms a potential secondary fluid and/or gas migration pathway in the near-surface, assuming that CO_2 will leak and reach this unit across three intervening aquitards and two aquifers. However, CO_2 would have to leak from the injection and/or observation wells directly into the Mannville Formation for this migration pathway to be effective, which is considered unlikely. Finally, a stratigraphic test hole, drilled to 293 m and abandoned in 1953, will be evaluated as an additional potential secondary CO_2 migration pathway in the near surface.

3. Conceptual model of the HARP SSSA

In addition to a good understanding of the geological and hydrogeological context of the HARP pilot site, there are several key features such as wells, surface activities and industrial activities, which form the focus of ongoing baseline characterization. Based upon characterization of these features, and associated risk assessment, specific targets for baseline and ongoing monitoring activities were identified. Such features may also be divided into those which are likely to change little over the course of the HARP project (e.g. groundwater chemistry), and those which will change annually (e.g. crop management), seasonally (e.g. mean soil CO_2 respiration and flux, mean soil temperature) or even on a daily basis (e.g. climatic conditions, soil moisture, precipitation, air quality). Soil temperature, moisture, gas composition and flux are highly variable depending upon climatic conditions. In addition to climatic effects, different soil compositions result in distinct differences in soil gas CO_2 concentration and flux associated with microbial and plant root respiration over a seasonal cycle [26].

Given the location and nature of the SSSA, the greatest natural variations in CO_2 concentration and flux are expected to be derived from soils; particularly when a combination of elevated moisture and temperature conditions prevail. Seasonally, spring and summer will therefore provide the highest natural CO_2 concentrations, derived from a combination of soil respiration, land management practices, local road traffic and nearby industrial activities. Carbon dioxide sources over the colder months are likely to be predominantly from local road traffic and industrial activities, and so a far lower CO_2 baseline concentrations are expected during the Fall and Winter periods.

Figure 3 summarizes the HARP SSSA conceptual model and includes available information on geology, from the Redwater-Leduc reef storage formation to the ground surface, groundwater composition, soil type and distribution, air quality and both natural and anthropogenic CO_2 sources and sinks.

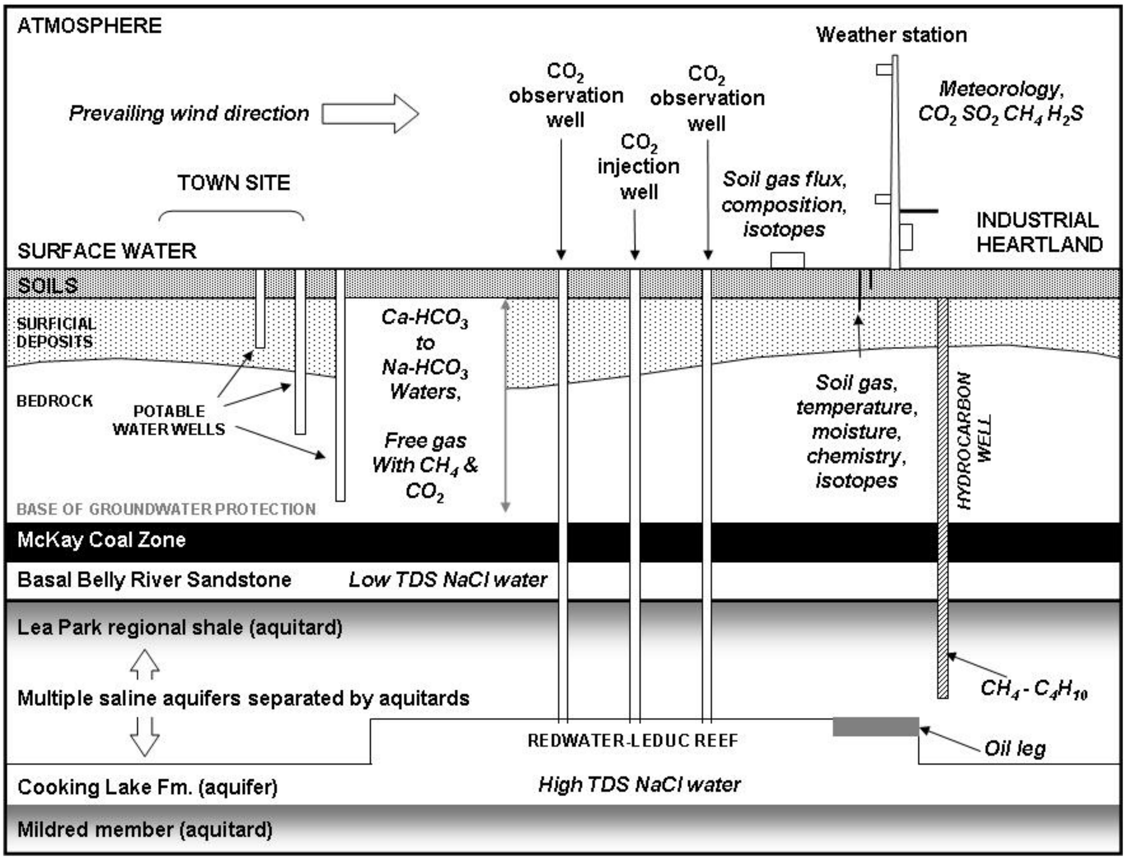

Figure 3: Summary of the HARP SSSA conceptual model. The monitoring strategy and implementation are based upon the various potential CO_2 sources and sinks in the area, along with specific targets such as potable water wells, hydrocarbon-related wells and CO_2 injection and observation wells.

4. Assurance Monitoring Approach

HARP assurance monitoring activities form one component of the broader MMV program, which will include a number of operational monitoring activities designed to determine the fate of injected CO_2 within the Redwater-Leduc reef. In addition to formation pressure, temperature and fluid compositions, geophysical surveys (surface-based and down-hole measurements) as well as surface deformation testing may be carried out [*pers. Comm.* ARC Resources Ltd., 2010]. Assurance monitoring activities will focus upon the various components of the HARP system summarized in Figure 3. Integration of assurance monitoring activities with operational monitoring of CO_2 injection, surface based and downhole geophysics will provide a robust MMV package.

Historical data related to air, soil and groundwater quality measurements within the SSSA have been collated where available. Specific sources of information include the National Research Council of Canada [27] and existing regional air quality monitoring programs such as the Fort Air Partnership [28], Alberta Environment [29] and Environment Canada [30] monitoring stations. Data collection to supplement these parameters is ongoing within the HARP SSSA as part of assurance monitoring baseline development. Specifically, soils, soil gas and soil moisture are being sampled and analyzed for physical and chemical composition, isotopic signature and also agricultural parameters of interest to local landowners.

Important dynamic features for this area include meteorological parameters such as precipitation, air temperature, wind speed, wind direction, relative humidity and barometric pressure. To capture variations in site conditions, a highly instrumented meteorological station will be equipped with open-path CO_2 sensors, as well as an eddy covariance module to determine atmospheric CO_2 concentration and net flux within the immediate vicinity. This system will be used to collect continuous air quality and meteorological data downwind of the proposed injection well location. Local air quality (including NO_2 and H_2S) will also be monitored to allow a comparison with regional air quality monitoring stations managed by Alberta Environment, Environment Canada and the Fort Air Partnership.

Near-surface bedrock and surficial aquifers are already being sampled quarterly for major and trace elements, isotopic composition, free gases, dissolved gases and other general indicators of water quality such as microbiology.

Spatial information related to the site is stored in a Geographic Information System (GIS) database specifically designed for the HARP project. This database acts as a repository for existing data, and also a data management and assessment tool for newly-acquired monitoring data. Continuously collected data, such as meteorological conditions, atmospheric CO_2 concentration and flux, may be used to update existing maps to create a series of physical and chemical snapshots of the HARP site-scale area at user-defined intervals. Periodic surveys will also be conducted to gather additional samples for physical and chemical analysis. This data will be used to augment information acquired by permanent monitoring equipment at the pilot site.

For the purposes of summarizing data and reporting as part of the HARP assurance monitoring schedule, comparisons will be made using continuously acquired data, supplemented by field survey information. A full assurance monitoring baseline will be in place by Spring 2011.

5. Public consultation

For landowners within the HARP LSSA, key questions naturally revolve around potential consequences of near surface CO_2 leakage on crop productivity, soil and air quality, and groundwater quality. The HARP assurance monitoring team, working alongside the operator of the site (ARC Resources Ltd.), is addressing these questions via a combination of site characterization, periodic monitoring and supplemental experimental studies on soil interaction. These tasks determine the site-specific effects that elevated CO_2 may have within waters, soils and the atmosphere. Detailed knowledge of local soil types, characteristics of surficial and bedrock formations and potable water composition allow numerical simulation of CO_2 leakage and potential geochemical effects. Periodic monitoring of these parameters provides baseline information, and assurance that conditions will not have not changed since the start of CO_2 injection. Experimentally, HARP area soils are being physically and chemically characterized and evaluated to assess the overall CO_2 buffering capacity of the soil matrix, along with information about the changes expected (if any) should CO_2 seepage occur.

The approach to link landowner and stakeholder consultations with the development of a baseline monitoring strategy is allowing for improved pubic understanding of the project and also the development of a robust monitoring approach. Not only are Carbon Capture and Storage (CCS) assurance monitoring samples being taken, but information on potable water quality, soil productivity and air quality are being provided to local community stakeholders to allow cumulative effects to be assessed, and continued sustainable development of industry and agriculture in Alberta's Industrial Heartland area. For example, following each field sampling survey, a summary report of groundwater quality is provided to each landowner for their reassurance that water quality has not been affected. Farmers within the HARP SSSA will also receive a nutrient recommendation report based upon the baseline quality of their soils, providing synergy between local land use optimization and the CO_2 storage pilot.

6. Preparation for Potential Project Upscaling

Logistically, the upscaling and associated time, resources and expense of monitoring activities for large CCS sites will become a potential issue. As discussed, pilot-scale monitoring activities are currently focussed within the HARP SSSA. Should the HARP pilot scale study prove to be successful, specifically with respect to CO_2 injectivity, CO_2 storage operations may be scaled up to allow the injection of larger quantities of CO_2 (*e.g.* up to 1 million tonnes of CO_2 per year). To anticipate potential monitoring-related issues within the HARP program, detailed information is currently being collated and interpreted from the entire Redwater-Leduc reef area (> 600 km^2) in preparation for the extension of current monitoring area limits. Tools such as CO_2 net flux determination by eddy covariance, and also open path laser CO_2 measurements, are being evaluated as potential technologies for large area measurements.

In addition to extended site characterization, risk assessment and monitoring activities, supporting laboratory experiments on site specific soils collected from the HARP area are being conducted to allow the prediction of CO_2 concentration and flux from soils across the pilot site as a function of meteorological conditions, soil temperature, soil moisture and soil composition. This method is being developed as a predictive soil gas screening tool to assess the extent of natural soil CO_2 production from similar soils under the range of environmental conditions expected, and across large areas.

7. Conclusions

Based upon the conceptual model of the HARP site and numerical prediction of the CO_2 plume behaviour within the Redwater-Leduc Reef, an assurance monitoring strategy has been defined. This strategy is integrated with the larger MMV program for the HARP pilot site, allowing pre-injection baseline conditions to be established from the deep injection formation to near-surface potable aquifers, soils and atmosphere. Following initial CO_2 injection, a combination of continuous site monitoring, supplemented by periodic field surveys, will provide time-series comparisons of all components of the geological storage system, and assurance to the public, government and other stakeholders that the injected CO_2 is acting as predicted, and that there are no negative effects on near-surface aquifers, soils or air quality.

Acknowledgement

The authors gratefully acknowledge the financial support from Natural Resources Canada (NRCan), the Alberta government and industry sponsors: BP, Suncor, Statoil and Total. The authors also acknowledge the help and support provided by local landowners in providing access for water and soil sampling throughout the year.

References

[1] Watson TL. Evaluation of Wellbore Integrity in Wells Penetrating the Redwater Reef. Report prepared for the Alberta Research Council, 2009.

[2] Gunter WD, Bachu S, Palombi D, Lakeman B, Sawchuk W and Bonner D. Heartland Area Redwater reef saline aquifer CO_2 storage project. 2009; Energy Procedia 1 (2009a), 3943-3950.

[3] Gunter WD, Bachu S, Buschkuehle, M, Michael, K, Ordorica-Garcia G and Hauck T. Reduction of GHG emissions by geological storage of CO_2: anatomy of the Heartland Aquifer Redwater Carbon Capture and Geological Storage Project (HARP), Alberta, Canada. 2009b; Climate Change Strategies and Management, Vol.1:2 (2009b) 160.

[4] Bachu S, Brydie J, Hauck T, Lakeman B, Palombi D, Stoakes, F, Wendte J, Lawton D, Darvish MP, Hawkes C, Chalaturnyk R., Krawec T and Sawchuck W. The Heartland Area Redwater CO_2 storage project (HARP): Results of Phase I site characterization. 2010; Tenth Conference on the Greenhouse Gas technologies (GHGT-10), Energy Procedia (2010).

[5] Strong, WL and Legatt KR. Ecoregions of Alberta. 1981; Alta. En. Nat. Resour., Resour. Eval. Plan Div., Edmonton as cited in: Mitchell, Patricia and Ellie Prepas (eds.). 1990. Atlas of Alberta Lakes. The University of Alberta Press. p12.

[6] Thornthwaite CW and Mather JR. Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance. Drexel Institute of Technology. Laboratory of Climatology. Publications in Climatology. 1957; 10(3):181-289.

[7] Hydrogeological Consultants Ltd.. County of Thorhild No. 7, Part of the North Saskatchewan River Basin, Townships 058 to 063, Ranges 18 to 23, W4M, Regional Groundwater Assessment. 1996; HCL File number 97-161.

[8] Hydrogeological Consultants Ltd.. County of Lamont No. 30, Part of the North Saskatchewan River Basin, Parts of Tp 051 to 058, R15 to 20, W4M. Regional Groundwater Assessment. 1999; HCL File Number 97-160.

[9] Hydrogeological Consultants Ltd.. Westlock County, Part of the Athabasca and North Saskatchewan River Basins, Parts of Tp 057 to 064, R23 to 27, W4M and R 01 to 03, W5M. Regional Groundwater Assessment. 2000; HCL File number 99-171.

[10] Hydrogeological Consultants Ltd.. Strathcona County, Part of the North Saskatchewan River Basin, Parts of Tp 050 to 057, R20 to 24, W4M. Regional Groundwater Assessment. 2001a; HCL File Number 00-179.

[11] Hydrogeological Consultants Ltd.. Sturgeon County, Part of the North Saskatchewan River Basin, Parts of Tp 053 to 058, R20 to 28, W4M & Tp 054 to 057, R 01, W5M. Regional Groundwater Assessment. 2001b; HCL File Number 01-110.

[12] Agriculture, Food and Rural Development. Annual Precipitation Summary from 1974-2001. 2008; (http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag7019?OpenDocument).

[13] Bowser, WE, Kjaersgaard AA, Peters TW and Wells RE. Soil Survey of the Edmonton sheet (83H). 1962; 2 maps at 1:126, 720 scale.

[14] Kjaersgaard, AA. Reconnaissance soil survey of the Tawatinaw map sheet (83I). 1973; Agriculture and Rural Development. 103 pages; 2 map sheets at 1:126:720 scale. http://www1.agric.gov.ab.ca.

[15] Hauck, TE, Peterson J, and Brydie J. Geological Mapping and 3D Modelling of the Sedimentary Succession in the Local-Scale HARP Area, Central Alberta. Alberta Innovates - Technology Futures, Edmonton, Alberta. 2010. Confidential Client Report.

[16] Power, B.A. and Walker, R.G., Allostratigraphy of the Upper Cretaceous Lea Park – Belly River transition in central Alberta, Canada. 1996; Bulletin of Canadian Petroleum Geology (44) 14-38.

[17] Dawson, FM, Evans CG, Marsh R and Richardson R. Uppermost Cretaceous and Tertiary strata of the Western Canadian Sedimentary Basin: In, Mossop, G. D. and Shetson, I. (comp), Geological Atlas of the Western Canadian Sedimentary Basin: Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary, Alberta, URL http://www.ags.gov.ab.ca/publications/ATLAS_WWW/ATLAS.shtml [19/03/08].

[18] Smith, D.G. Paleogeographic evolution of the Western Canada Foreland Basin. *In* Geological Atlas of the Western Canada Sedimentary Basin. G.D. Mossop and I. Shetson (comps.). 1994. Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council, p. 277-296.

[19] Andriashek L. Quaternary Stratigraphy of the Edmonton Map Area, NTS 83H. Open File Report #198804, Terrain Sciences Department, Natural Resources Division, Alberta Research Council, 1988.

[20] Stantec Consulting Ltd. Regional Assessment of the Groundwater Quality, the Beverly Channel in the Fort Saskatchewan Area. Prepared for: Northeast Capital Industrial Association. 2004; Report No. 1-02-15741.

[21] Stantec Consulting Ltd. Regional Assessment of the Groundwater Quality, the Beverly Channel in the Fort Saskatchewan Area, Phase II. Prepared for: Northeast Capital Industrial Association. 2006; Report Number 1102-17094.

[22] Total. Total Upgrader Project, Section 7: Groundwater, Volume 2: Environmental Impact Assessment. 2007; Total E&P Canada Ltd.

[23] NorthWest Upgrading. North West Upgrader Project Integrated Application for Approval and all Supplemental Information. Alberta Energy and Utilities Board Application, 2007; No. 1444141.

[24] Fekete Associates Inc. Development of the Second Petrel Static Model, its Calibration and Simulation of CO_2 Storage in the Redwater Reef, Alberta. Prepared by Fekete Associates Inc. for Alberta Research Council, November, 2009b. Confidential client report.

[25] Fekete Associates Inc. Calibration of the First Petrel Static Model and Simulation of Redwater Reef, Alberta., July 24, 2009, prepared by Fekete Associates Inc. for Alberta Research Council, July 2009a. Confidential Client Report.

[26] Janzen, HH. Carbon cycling in earth systems—a soil science perspective. Agriculture, ecosystems and environment. 2004; 104 (3):399–417.

[27] National Research Council of Canada. 2010. http://www.climate.weatheroffice.gc.ca/climate_normals/index_e.html

[28] Fort Air Partnership. 2010. http://www.fortair.org/

[29] Alberta Environment. 2010. http://www.weatheroffice.gc.ca/forecast/canada/index_e.html?id=AB

[30] Environment Canada. 2010. http://www.climate.weatheroffice.gc.ca/Welcome_e.html